Development of the Glenn-HT Computer Code to Enable Time-Filtered Navier-Stokes (TFNS) Simulations and Application to Film Cooling on a Flat Plate Through Long Cooling Tubes

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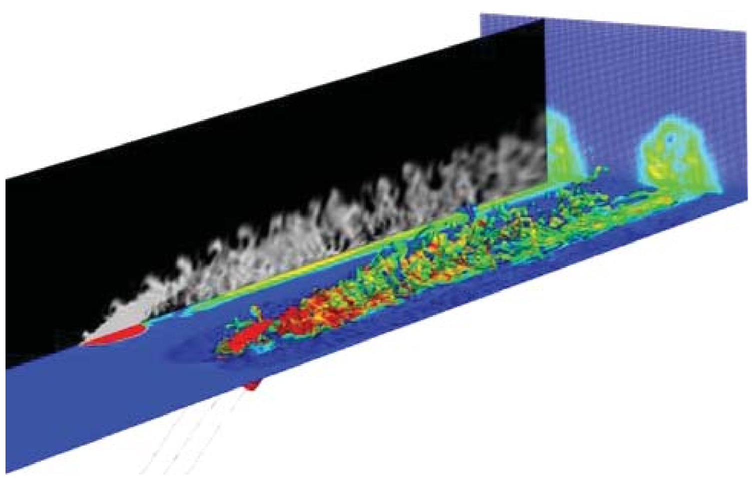


Motivation

- Prediction of effectiveness/ heat transfer coefficient due to film cooling is fraught with inaccuracies and large variations using turbulence models.
- This is exacerbated at higher blowing ratios (M>1)
- The high M regime is relevant to gas turbine blades.
- Good prediction in that environment is highly desirable to allow efficient use of coolant air and achieving high turbine efficiencies.

Plan

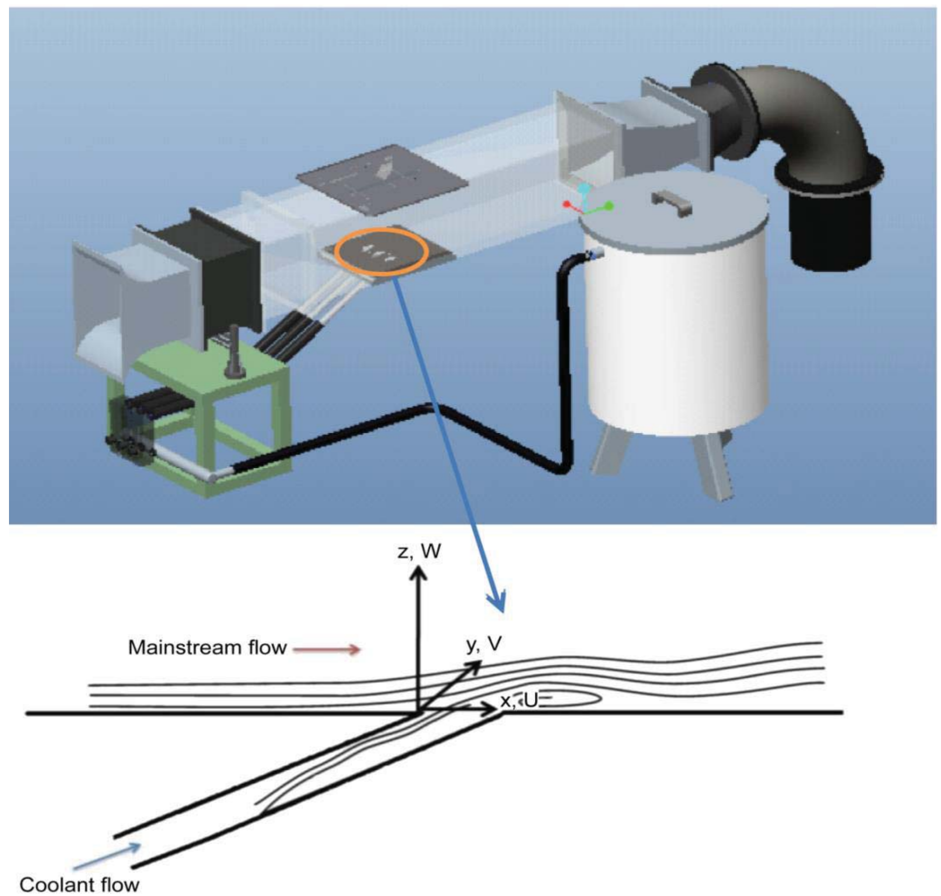
- Two-Pronged plan was conceived:
  - To perform accurate experiments measuring film-cooling effectiveness and the relevant flows.
  - To come up with CFD practice that is efficient and accurate.

Plan (Cont.)

- 30 times engine scale test facility
- A three hole (d=0.75”) film-cooling arrangement was adopted with a pitch of 3d’s and inclination angle of 30°
- Effectiveness varies with L/D and thus L/D was chosen to be large =20 to allow for fully developed flow in the tubes.
- This also removes the effect of the plenum flow shown to affect the results.

Conditions

- Free Stream Velocity= 9.1 m/s
- Reynolds number based on tube dia.= 11,000
- Inlet Tu=1.5%
- δ_{99} =0.67*d at X/d=-0.5



CFD Tool, Glenn-HT

- Full compressible Reynolds-Averaged Navier-Stokes Formulation and Conjugate Heat Transfer
- Multi-block structured grids
- Finite Volume formulation
- Second order central differencing, 4th order artificial dissipation with eigenvalue scaling or,
- Second order upwind schemes, Hunyh, AUSM
- Multi-stage explicit Runge-Kutta time integration with local time stepping
- Multi-grid convergence acceleration
- Dual-Time-Stepping for unsteady simulations
- Parallel processing via MPI

Why TFNS

- TFNS (PRNS, VLES) or ‘Time Filtered-Navier-Stokes,’ is an unsteady method. (Liu and Shih)
- Developed to simulate large turbulent eddies.
- Used with RANS relevant grid resolutions in combustion simulations with success. (Liu and Shih)
- Larger timescales (lower frequencies) of the turbulence are directly calculated while the effects of the unresolved turbulence timescales are modeled by a dynamic equation system.
- Contents of both resolved and unresolved turbulence are regulated by a Filtering Control Parameter (FCP), which is related to the *width* of the temporal filter.

More About TFNS

- TFNS equations and its subfilter model do not have grid spacing as a parameter in their formulations.
- Possible to achieve a grid-independent numerical solution for a fixed Filtering Control Parameter.
- TFNS enables performance of URANS, very large eddy simulations (VLES), LES, and even Direct Numerical Simulations (DNS) in a unified way through the judicious selection of the value of FCP and the appropriately refined grid.

Filtering

- Filtering is done via: $\bar{\phi}(t, x_i) = \frac{1}{\Delta_T} \int_{t-\Delta_T/2}^{t+\Delta_T/2} \phi(t', x_i) dt'$
- The ratio Δ_T/T is used to set the FCP.

  FCP= $f_i\left(\frac{\Delta_T}{T}\right) \approx 2\left(\frac{\Delta_T}{T}\right) - \left(\frac{\Delta_T}{T}\right)^2 \qquad i = 1, 3, 5$

- For example, $\Delta_T/T = 0.16$ produces an FCP = 0.30 is intending to **directly resolve turbulence scales responsible for** about **70% of the total turbulent kinetic energy** and **model the rest** of the unresolved turbulence scales that contain about **30% of the total turbulent kinetic energy**.
- An FCP of 0.3 was used in our computations.

Subfilter Model

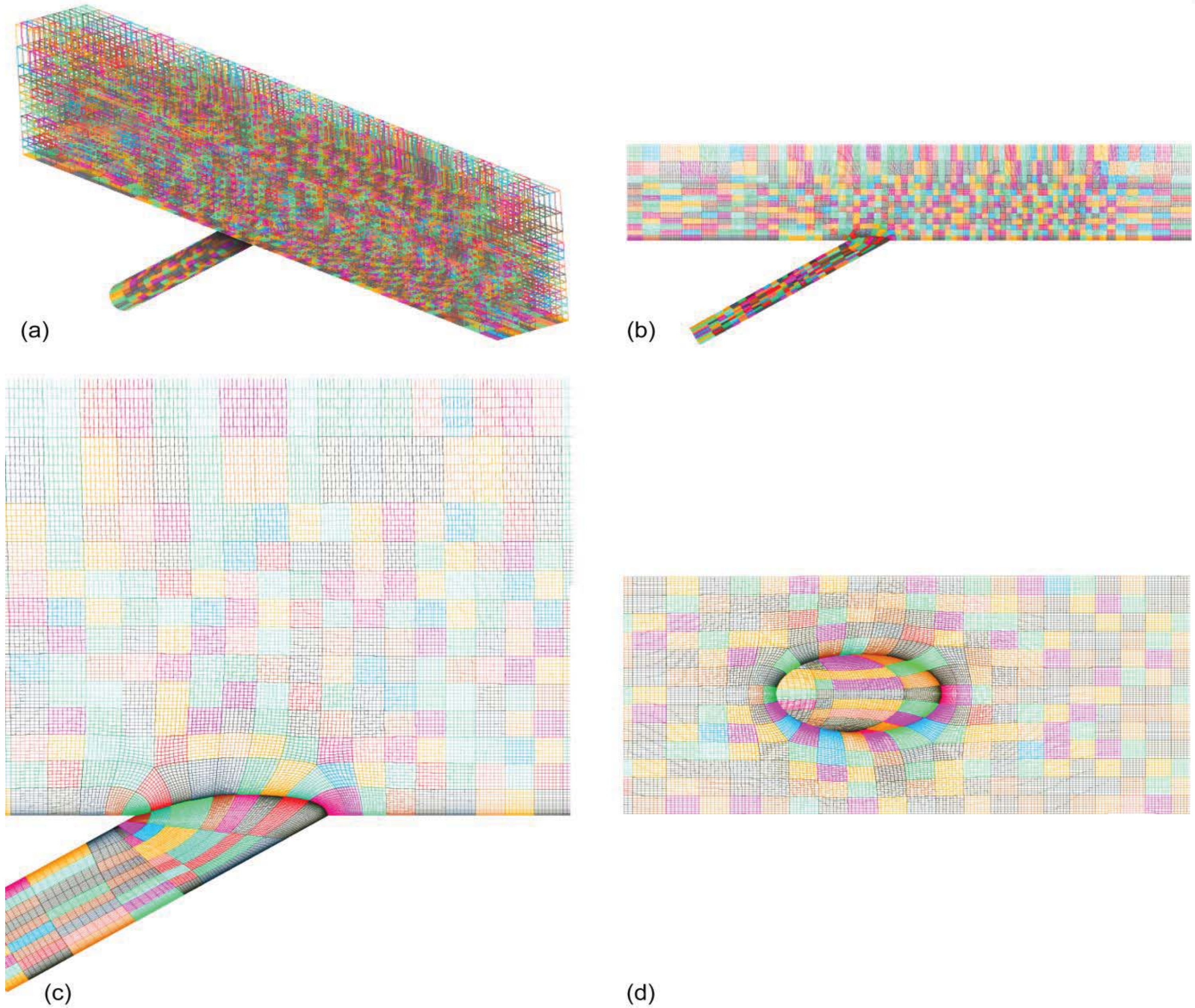
- The subfilter model uses a relationship between the unresolved turbulent stresses (Reynolds) and the resolved turbulent flow field.
- In addition to the dissipative and diffusive effects accounted for through the eddy viscosity, the subfilter model accounts for the effects of anisotropy and rotation.

$$\tau_{ij} = -2 f_1 \mu_T \left(\tilde{s}_{ij} - \delta_{ij} \tilde{s}_{kk} / 3 \right) + \frac{1}{3} \delta_{ij} \tau_{kk} - A_3 f_3 \bar{\rho} \frac{k^3}{\varepsilon^2} \left(\tilde{s}_{ik} \tilde{\omega}_{kj} - \tilde{\omega}_{ik} \tilde{s}_{kj} \right)$$

$$+ 2 A_5 f_5 \bar{\rho} \frac{k^4}{\varepsilon^3} \left[\tilde{\omega}_{ik} \tilde{s}^2_{kj} - \tilde{s}^2_{ik} \tilde{\omega}_{kj} + \tilde{\omega}_{ik} \tilde{s}_{km} \tilde{\omega}_{mj} - \tilde{\omega}_{kl} \tilde{s}_{lm} \tilde{\omega}_{mk} \delta_{ij} + II_s \left(\tilde{s}_{ij} - \delta_{ij} \tilde{s}_{kk} / 3 \right) \right]$$

$$\overline{\theta u_i} = -\kappa_T T_{,i} - \kappa_T \frac{k}{\varepsilon} (C_1 S_{ij} + C_2 \Omega_{ij}) \quad ; \kappa_T = \frac{\mu_t}{\mathrm{Pr}_t}$$

Computational Domain



Computational Details

The computational domain:

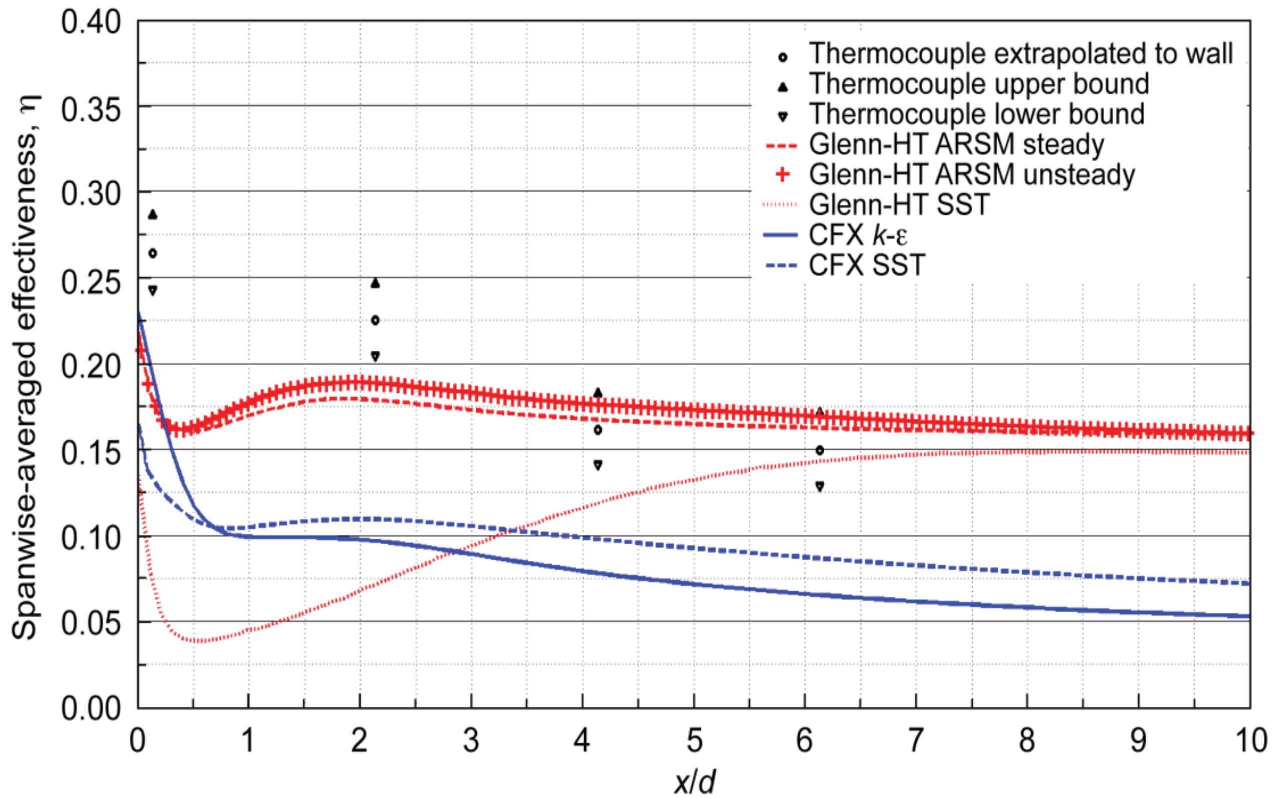
- One full hole modeled.
- Multi-block grid contained approximately 8 million cells.
- From12 d’s upstream to16 d’s downstream of the cooling hole.
- Spacing between the holes 3d’s.
- Periodic b.c. in spanwise direction.
- Free-Stream b.c. at 5d’s from the wall.
- Exit boundary condition specified at the outlet on the domain.
- The *Tu* (1.5 percent as measured) and a turbulence length scale were specified at the inlet.
- No particular handling of the inlet boundary condition to include unsteadiness for our TFNS computations was performed.

Computational Details (Cont.)

- Multiple block groups were assigned to individual CPUs for balanced parallel computing.
- Smaller blocks were further consolidated to reduce communications overhead before implementing grouping.
- Initially 120 groups (CPUs) were used.
- It was possible to increase that number to 1200 for improved parallel capability.
- Grid refinement in areas near the no-slip walls and the cooling hole outlet and downstream of the cooling hole with wall shear-stress-scaled grid spacing of $\Delta x^+ < 300$, $\Delta y^+ < 3$, $\Delta z^+ < 200$.
- Grid cells in the film cooling flow core were constructed to be uniform and nearly cubic in shape.

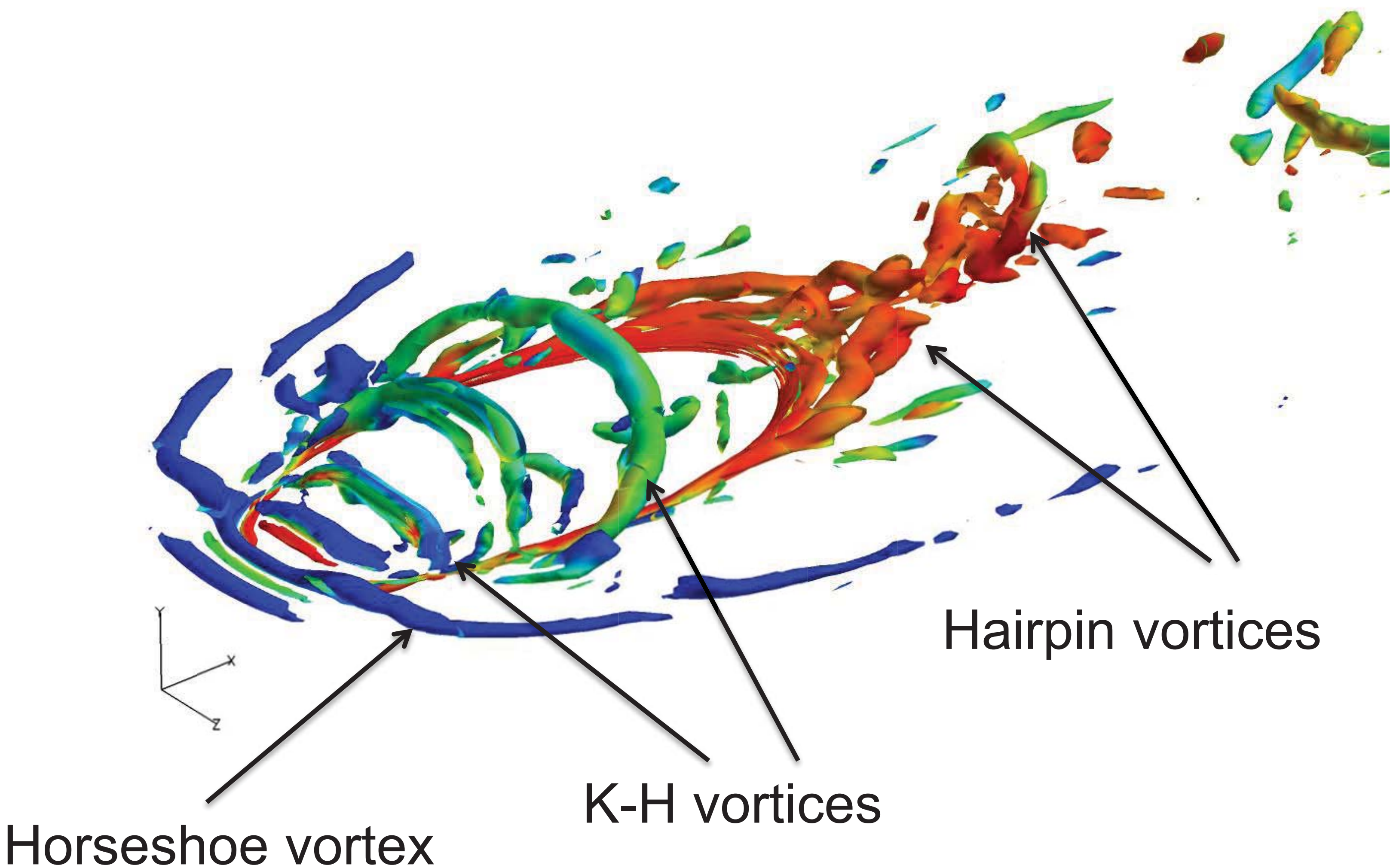
RANS and URANS

$\eta = (T_\infty - T_{aw})/(T_\infty - T_c)$

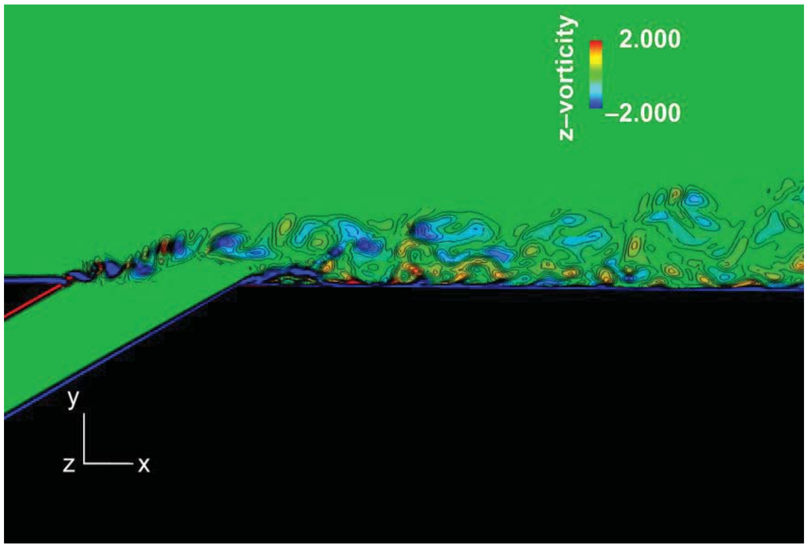


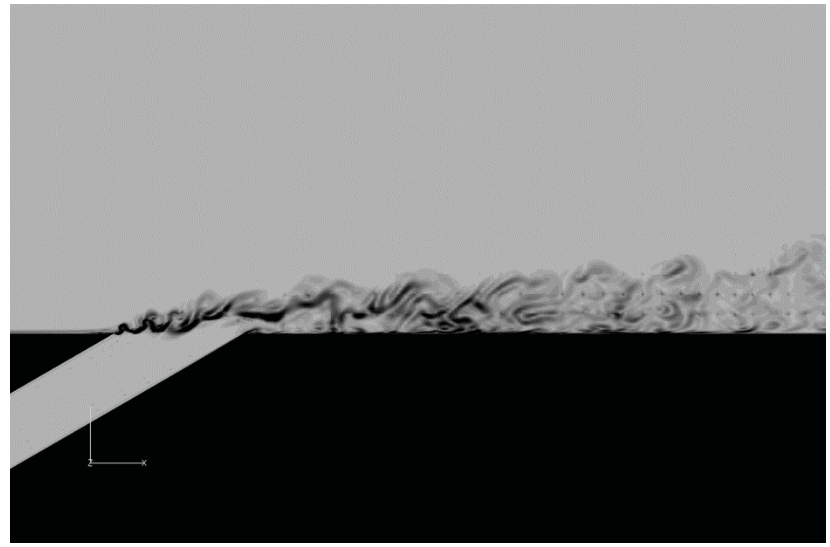
- For the M=1, DR=1 case, multiple computations were performed using RANS and URANS to show the variation in the results obtained and show the need to reduce the impact of turbulence models.

TFNS Solutions-M=0.5, DR=1.0



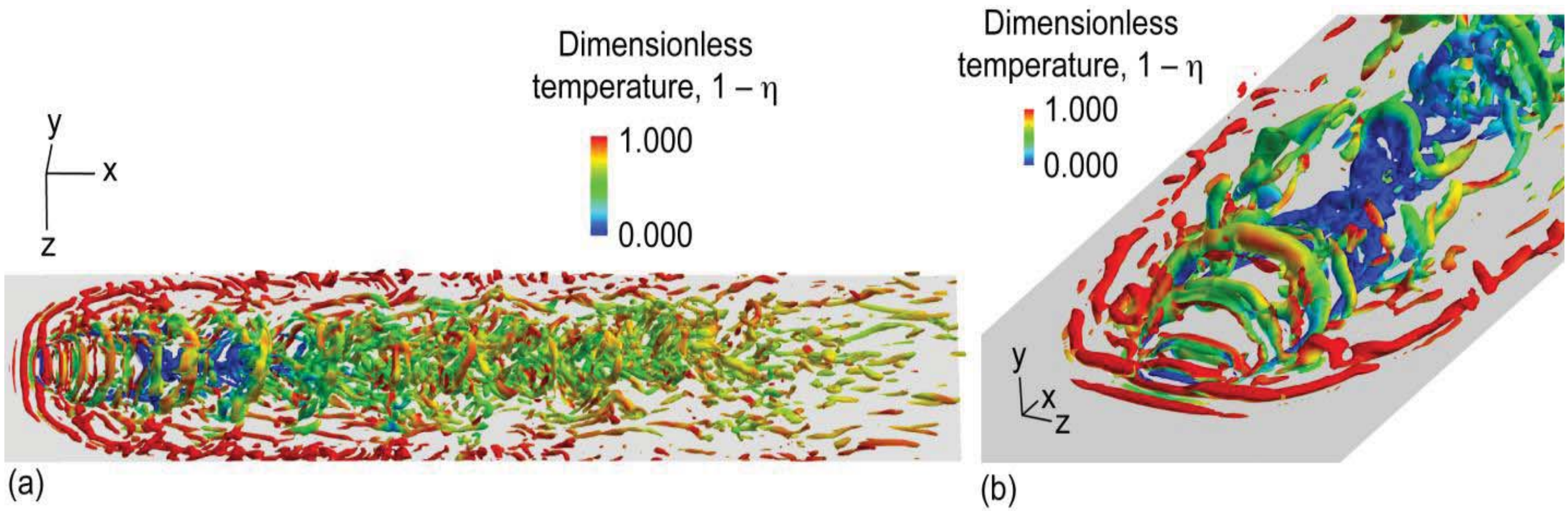
TFNS Solutions-M=0.5, DR=1.0





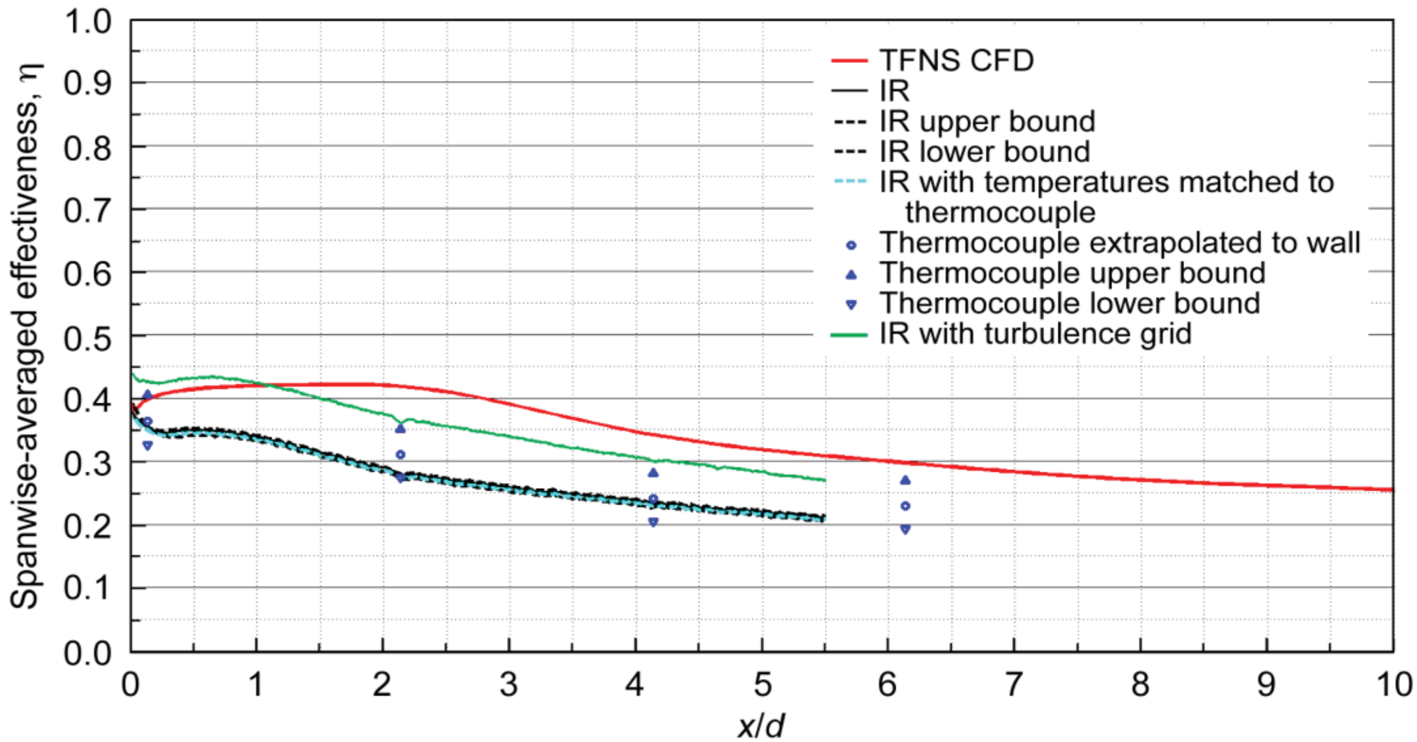
- Figure shows , Z-vorticity and Density Gradient.

TFNS Solutions-M=0.5, DR=1.0



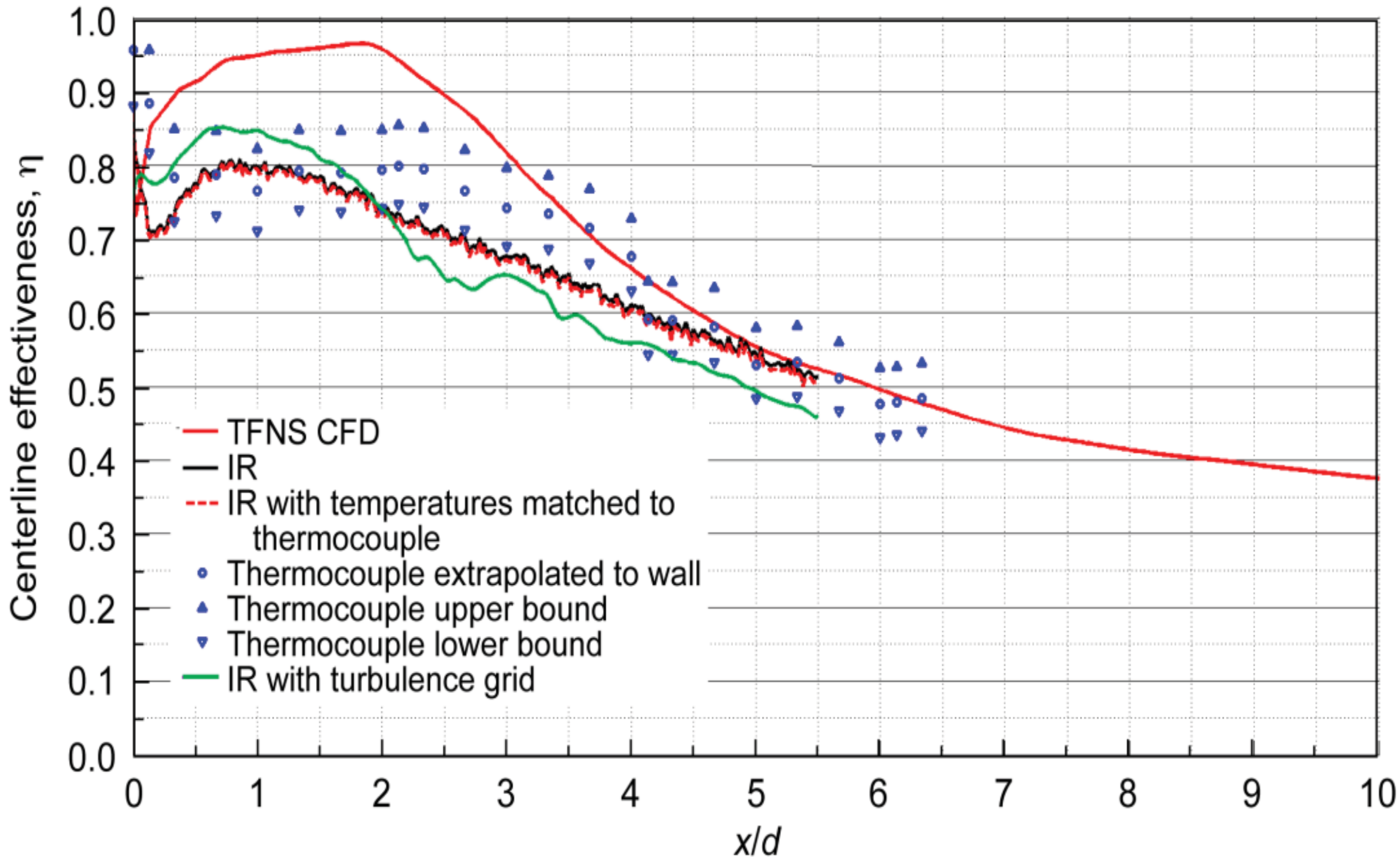
- *Q*-criterion isosurfaces of Q^* = 0.1 at M = 0.5 and DR = 1.0.
- Note the Kelvin-Helmholtz vortices.
- Hairpin vortices.

TFNS Solutions-M=0.5, DR=1.0



- Comparison to data shows over prediction!

TFNS Solutions-M=0.5, DR=1.0



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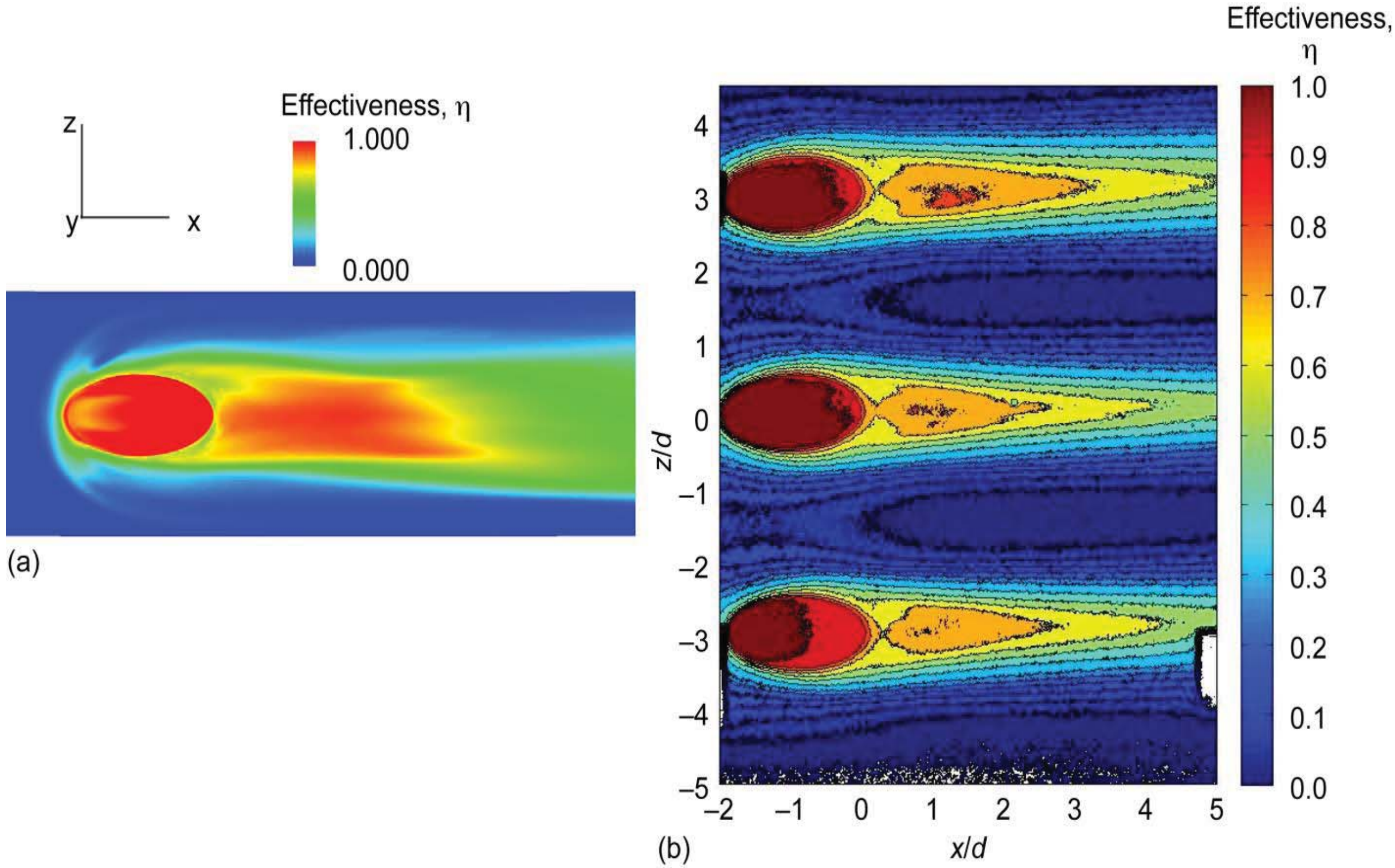
TFNS Solutions-M=0.5, DR=1.0



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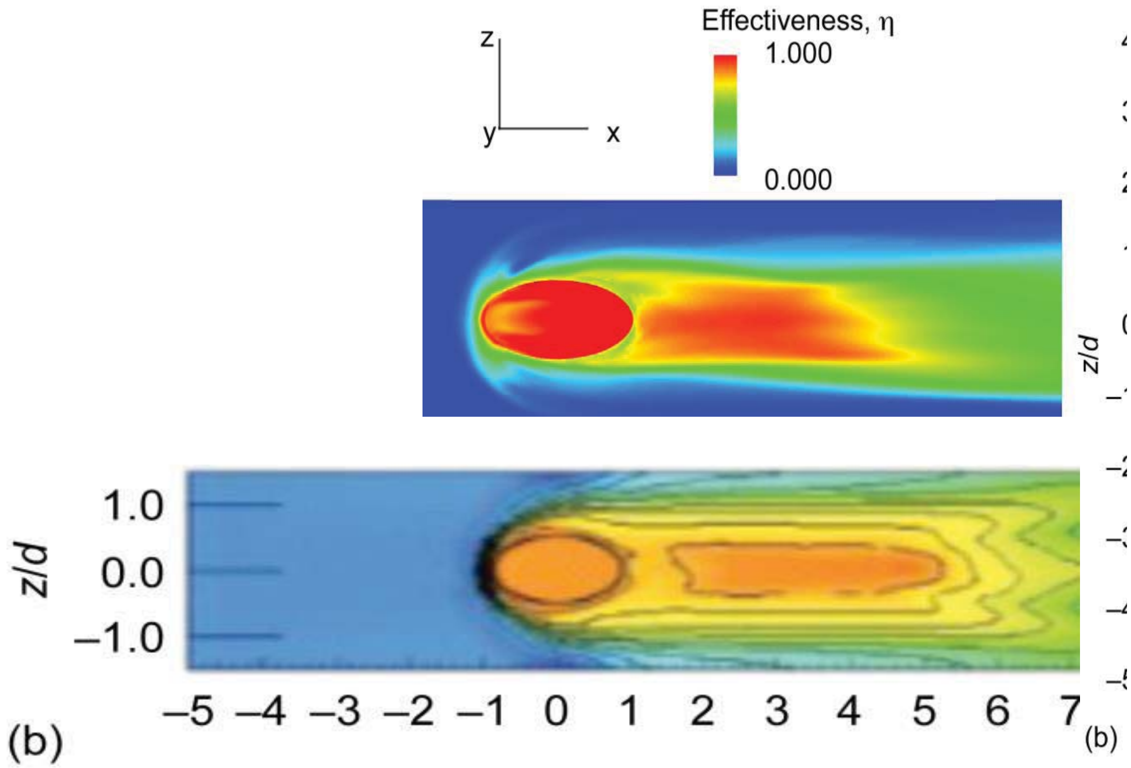
TFNS Solutions-M=0.5, DR=1.0

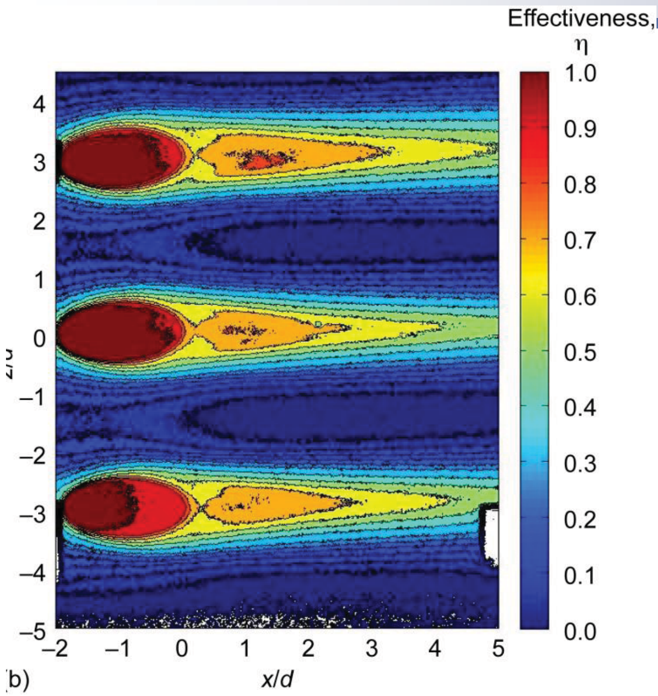


TFNS—Without FS turbulence

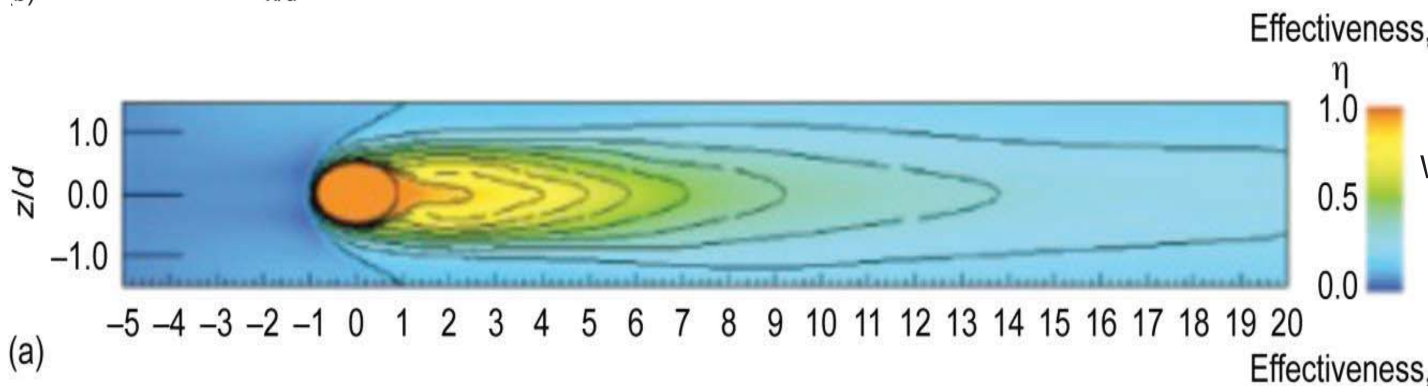
No Crossflow Turbulence

Ziefle, J.; and Kleiser, L.: Numerical Investigation of a Film-Cooling Flow Structure: Effect of Crossflow Turbulence. J. Turbomach., vol. 135, no. 4, 2013, pp. 041001—041001–12.

TFNS Solutions-M=0.5, DR=1.0



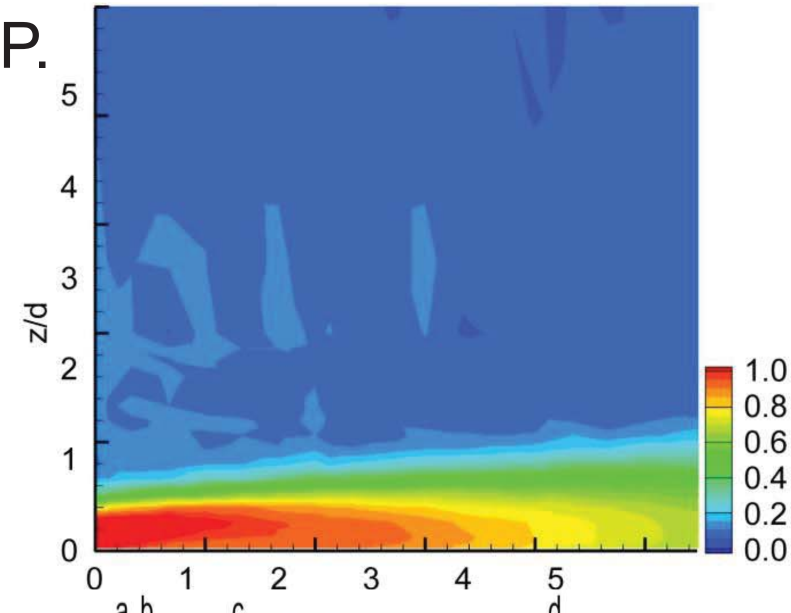
EXP.

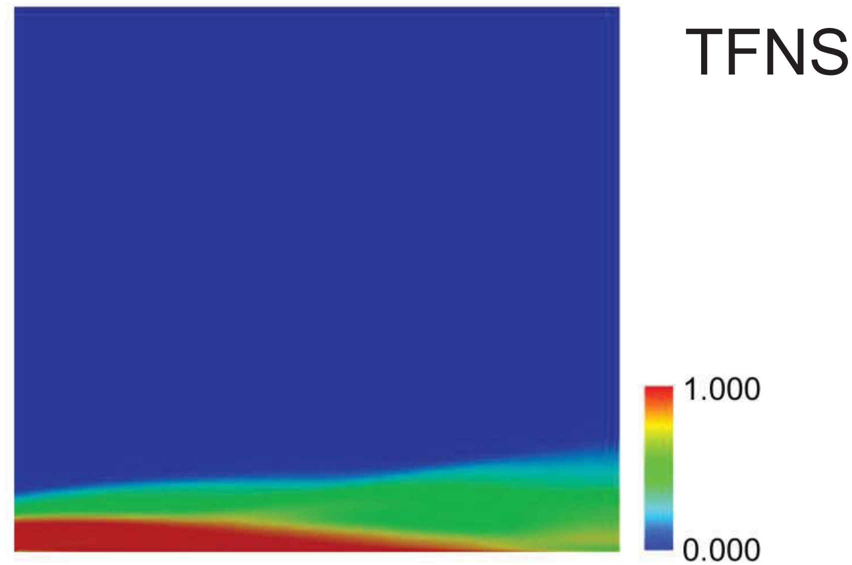


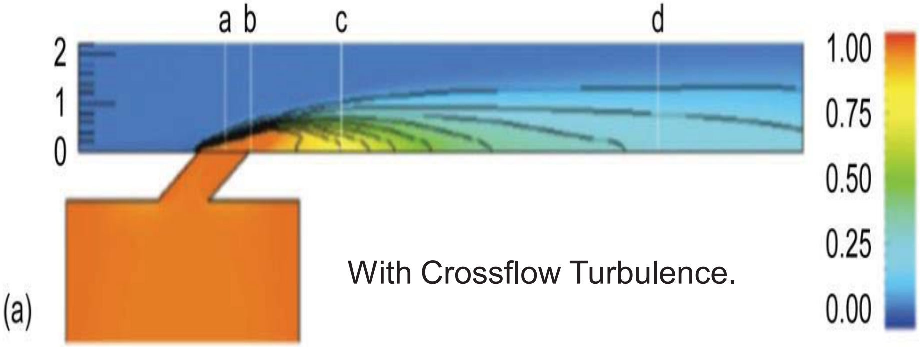
With Crossflow Turbulence.

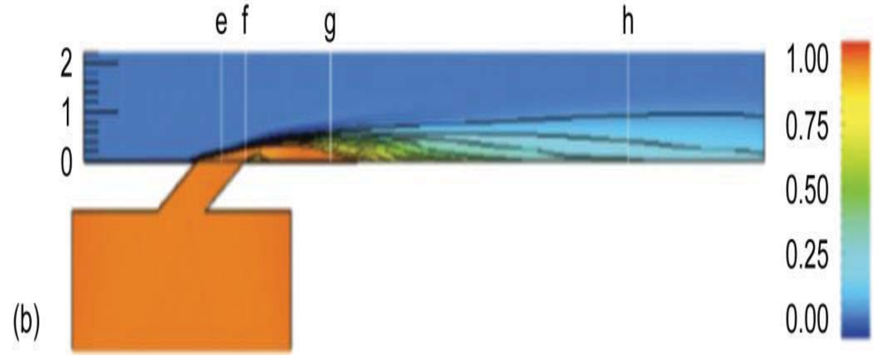
Ziefle, J.; Kleiser, L.: Numerical Investigation of a Film-Cooling Flow Structure: Effect of Crossflow Turbulence. J. Turbomach., vol. 135, no. 4, 2013.

TFNS Solutions-M=0.5, DR=1.0



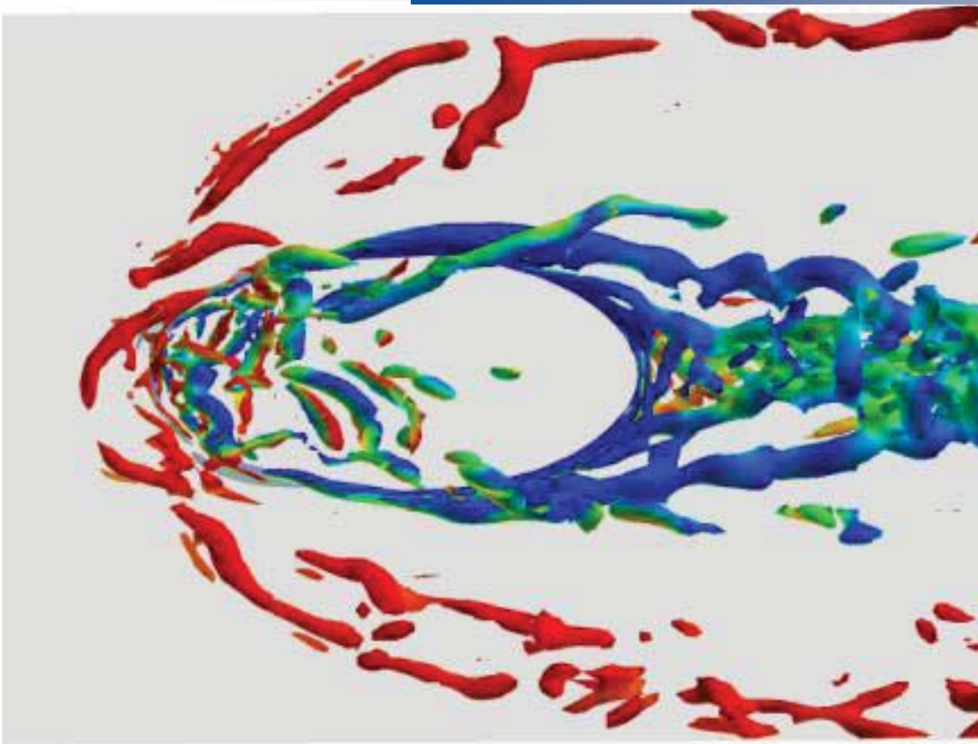


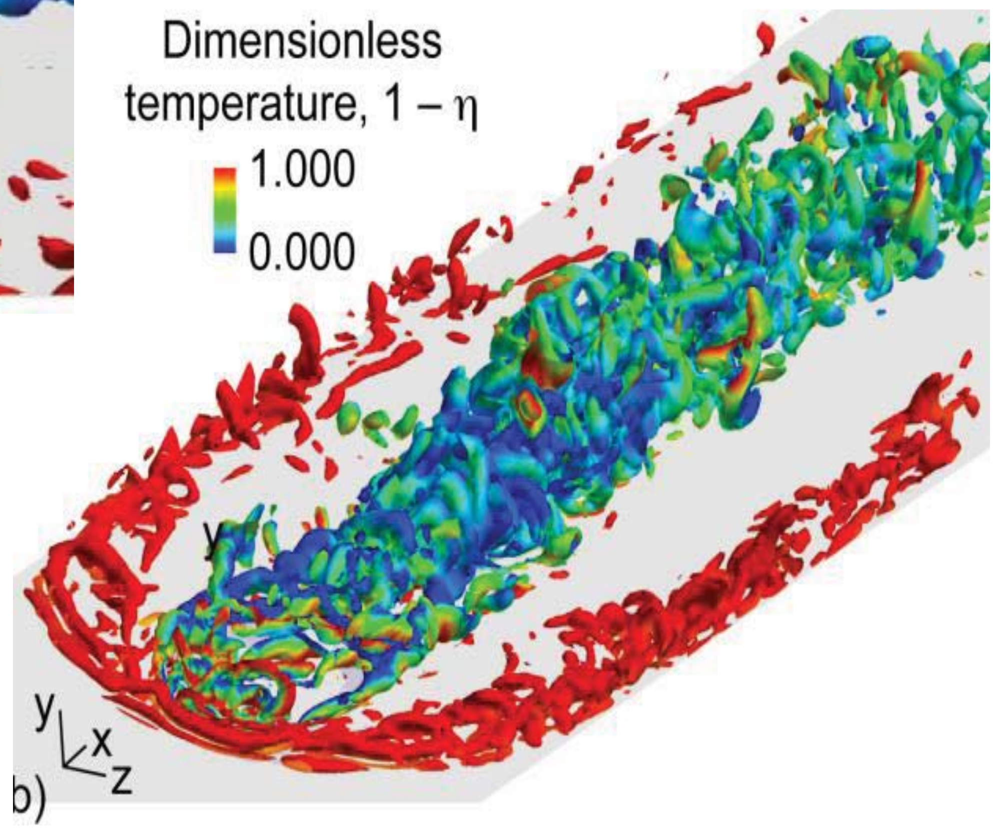




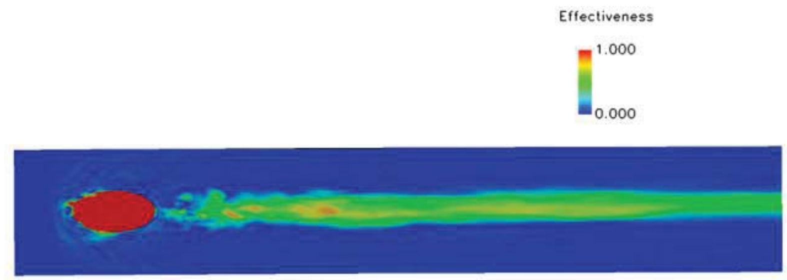
Ziefle, J.; and Kleiser, L.: Numerical Investigation of a Film-Cooling Flow Structure: Effect of Crossflow Turbulence. J. Turbomach., vol. 135, no. 4, 2013, pp. 041001—041001–12.

TFNS Solutions-M=1.0, DR=1.0

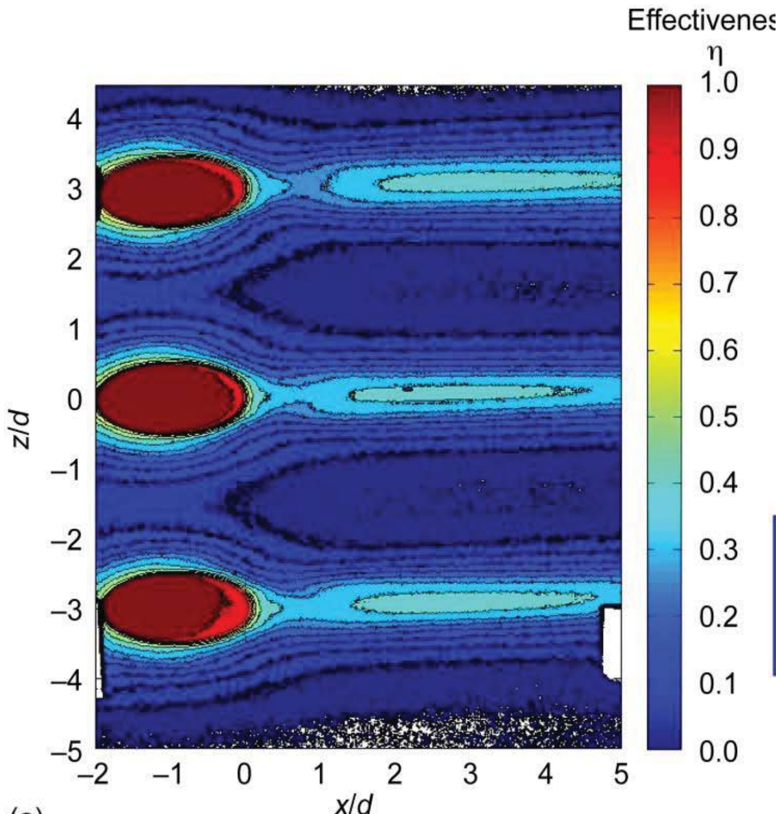




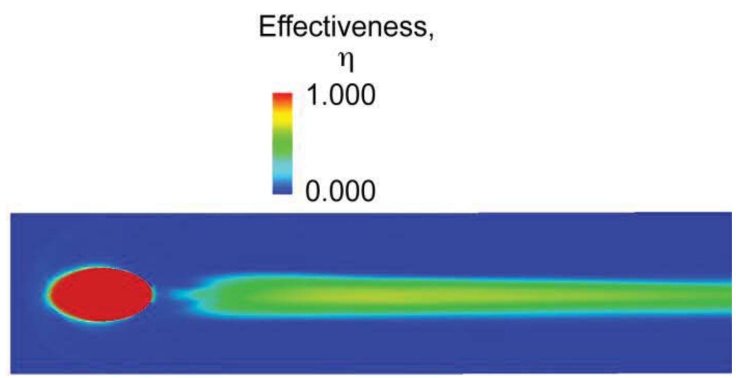
TFNS Solutions-M=1.0, DR=1.0



TFNS, Instantaneous



(a)

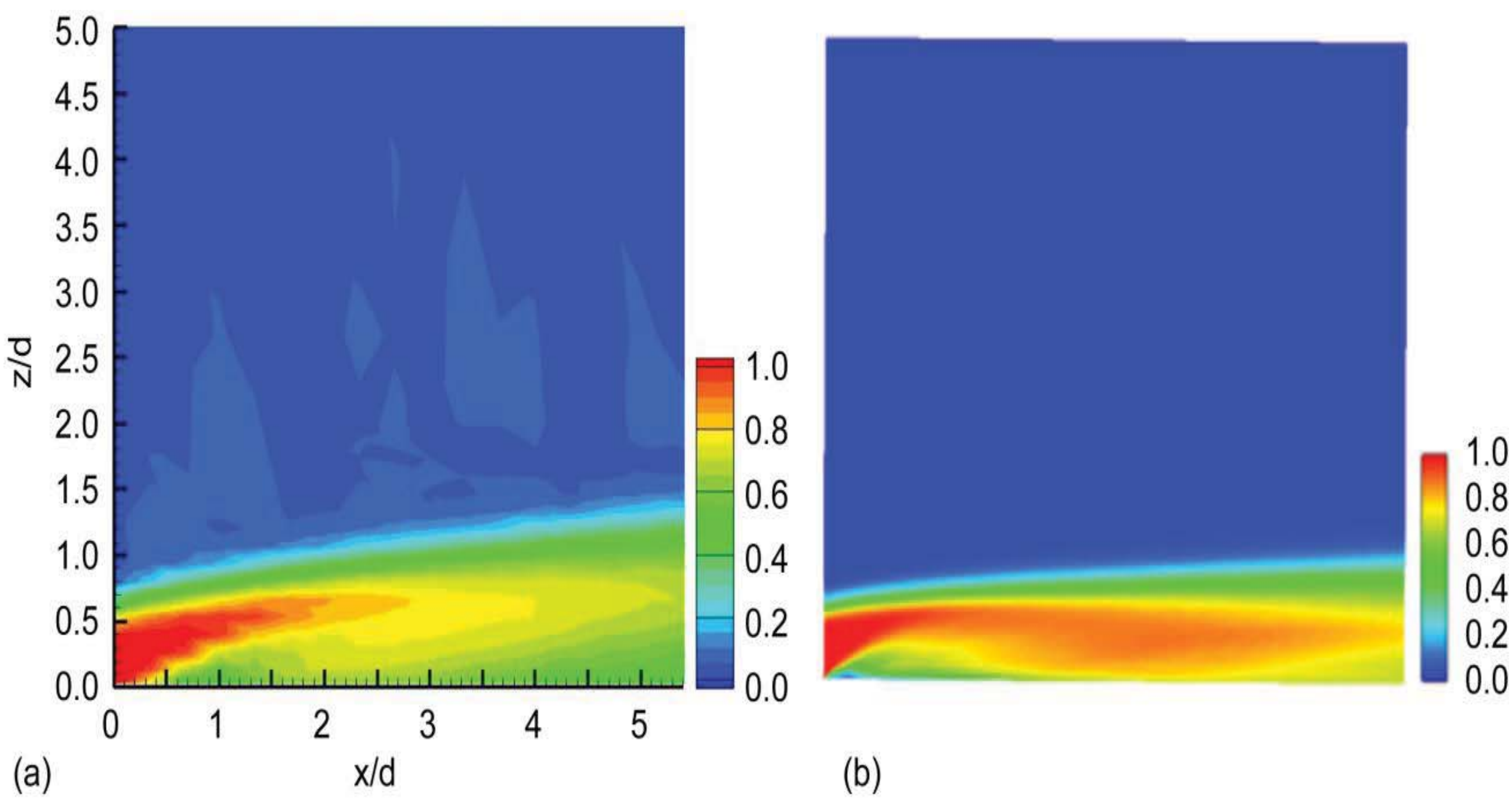


(b)

EXP.

TFNS, Time Averaged

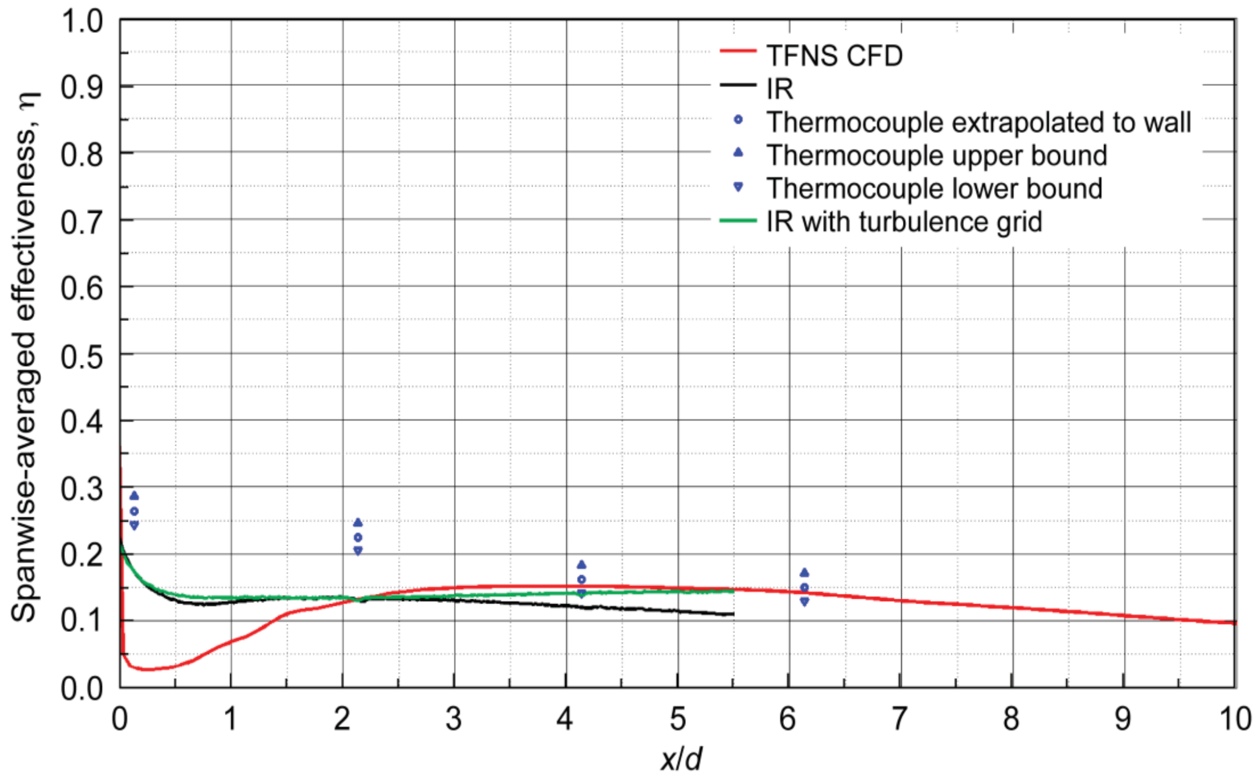
TFNS Solutions-M=1.0, DR=1.0



EXP.

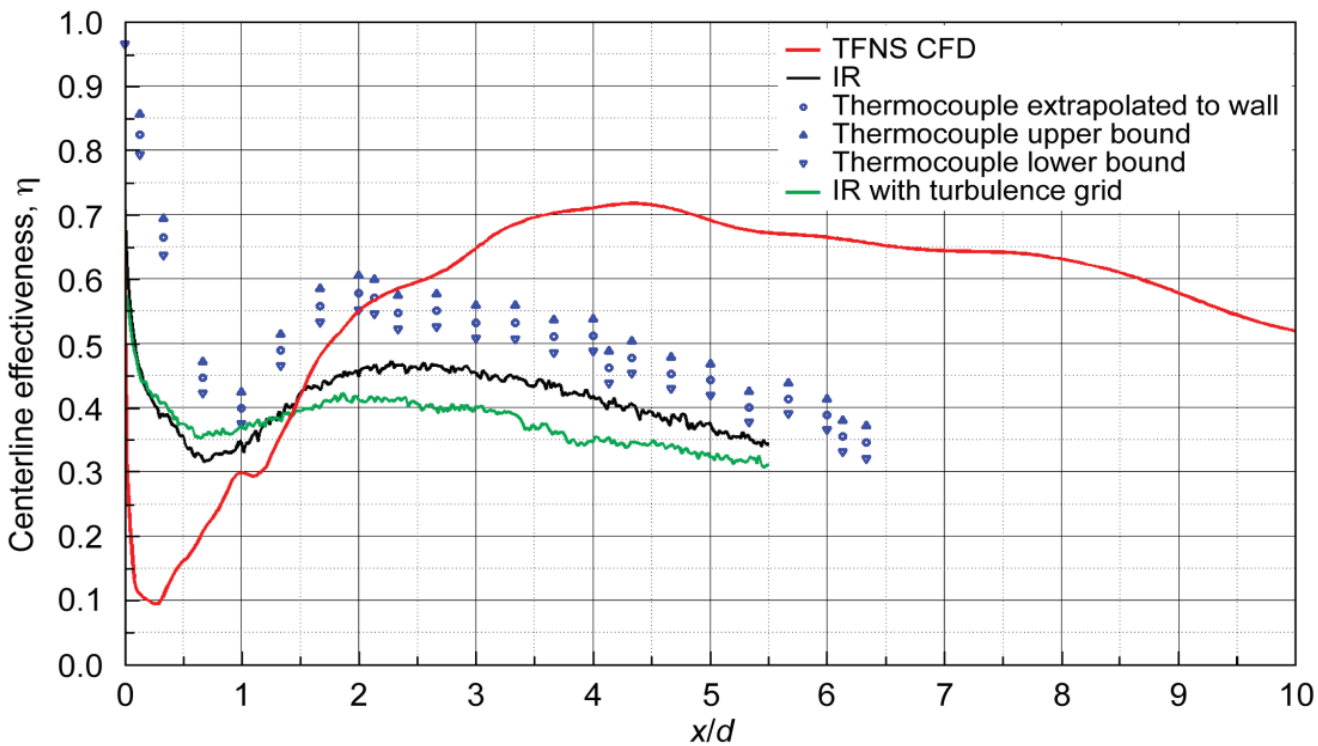
TFNS

TFNS Solutions-M=1.0, DR=1.0



Spanwise-averaged film effectiveness for *M* = 1.0, *DR* = 1.0, and *Tu* = 1.5

TFNS Solutions-M=1.0, DR=1.0



Centerline film effectiveness for
M = 1.0, *DR* = 1.0, and *Tu* = 1.5

Summary and Conclusions

- The Time-Filtered Navier-Stokes (TFNS) method was implemented in the Glenn-Heat Transfer (Glenn-HT) code.
- Analyses of a flat plate cooled by long holes inclined at 30° to the free stream were conducted to obtain both steady and unsteady flow solutions.
- The experimental data from an accompanying experiment.
- Results showed that RANS solutions are highly dependent on the turbulence model used and URANS does not provide a better alternative.

Summary and Conclusions

- To reduce this dependence, the unsteady TFNS was used.
- Good resolution of the flow was achieved: K-H structures resulting from the interaction of the two streams and hairpin vortices among others can be observed.
- Good agreement was not achieved to the IR thermography.
- Based on the literature for the blowing ratio of 0.5, it was concluded that achieving a successful agreement requires accurate matching of the free-stream turbulence.
- Results of the TFNS, are consistent with computations performed in the literature without the effect of free stream and appropriate boundary conditions should be implemented in the flow solvers.